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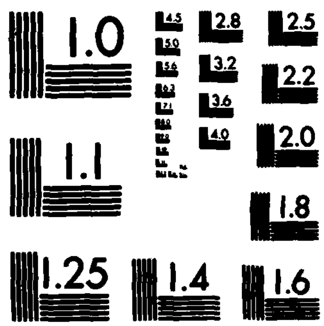
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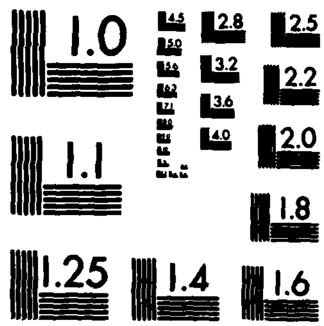
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COMPUTER-BASED SIMULATIONS FOR MAN-COMPUTER SYSTEM DESIGN

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INTRODUCTION

The Human Engineering Division of the Air Force Aerospace Medical Research Laboratory (AFAMRL) has used man-in-the-loop simulations to investigate human factors problems posed by man/computer interactions in proposed weapon system concepts. Two of the system contexts in which computer-based simulations have been used are command-control and digital avionics. Two command-control experiments and one cockpit design experiment will be summarized in this paper. The final section of the paper is concerned with generic principles for user-oriented man-computer system design.

SURVEILLANCE FUNCTION SIMULATION

Background

This simulation was programmed on an IBM computer complex which included four graphic display units and an analog-to-digital conversion capability. The complex was configured to provide real-time command-control system simulations for research purposes (1). The surveillance function program used approximately 145K bytes of core and operated on a 10.8-second recurrence cycle, which approximated radar antenna scan rates.

The purpose of this simulation was to represent air surveillance capabilities based on time-compressed, digitized radar returns which formed "trails" corresponding to aircraft flight paths. Through parametric control the simulation could be tailored to represent a variety of surveillance system configurations. The configuration used in experiments to be summarized below was patterned after the USAF Airborne Warning and Control System (AWACS). It allowed up to four operators to perform the surveillance function simultaneously via the four graphic display units.

Simulation parameters which could be manipulated as independent variables included time of radar return entry, location of entry and exit, speed of trail, length of trail or "history," and type of return, i.e., friendly aircraft, search (unidentified aircraft), or false report (clutter). The parameters could be combined to represent different enemy attack strategies, target introduction rates, and false report densities. Radar return errors and blip/scan ratios also could be varied statistically. Surveillance crew size and workload allocation could also be changed as independent variables.

The simulated radar returns took the form of "blips," or short dashes, illuminated on the CRT display. Radar trails were presented in ripple fashion, with the oldest return in the history presented first and followed successively by more recent returns. The operator was required to initiate automatic tracking on "target" returns by "lightpenning" the most recent return and assigning a numeric signature via keyboard entries. A vector, or track, was automatically displayed at the last return to indicate heading (by orientation) and velocity (by length).

When automatic tracking failed (in accordance with programmed statistical parameters), the operator performed "track maintenance" by repeating the initiation procedure. The need for track maintenance occurred when the track (vector) "drifted" out of association with the trail.

Experiment Design

One of several human factors studies accomplished with the computer-based surveillance simulation involved the use of university students extensively trained on the simulation to investigate the effects of trail length, blip scan ratio (number of scans on which a return was received from a target aircraft divided by the total number of scans), and crew size (2). The experiment design was a three-factor factorial with four replications. Three levels of each were investigated: trail lengths of five, seven, and nine returns; blip scan ratios of .5, .7, and .9; crew sizes of one, two, and three operators.

Each experimental trial was comprised of a 28-minute mission. Simulated aircraft entered a 200 × 200 nautical mile surveillance area at an average rate of two per minute (standard deviation = .75 per minute) at an average speed of 500 knots. Radar return error was programmed as a Rayleigh distribution with a standard deviation of one nautical mile. Probability of track failure (drift out) was .13 and the false report, or "clutter" rate was two per scan per point of trail history.

The efficiency of surveillance performance was assessed via a number of automatically recorded dependent variables. These measures included: initiation time for each trail, percent of trails initiated, percent of trails reinitiated or maintained correctly, and percent of scans with good tracking. First good initiation was calculated by subtracting the time of the scan on which the return from an aircraft appeared on the display from the time of the scan during which an effective initiation of automatic tracking was achieved. These values were summed and divided by the total aircraft entering the "surveillance area" to obtain a mean initiation time score for each 28-minute session. Percent of aircraft correctly initiated was determined for each session by dividing the total number of aircraft trails on which automatic tracking was effectively initiated at least once by the total number of aircraft which entered the surveillance area. Percent of scans with good tracking was the ratio of the number of scans with good tracking (correct track and signature block, correct heading, etc.) on each aircraft, summed across all aircraft passing through the surveillance area, to the number of scans made on each aircraft summed across all aircraft entering the area during the session.

Results

Analyses of variance were used to test for significant effects of the independent variables. The effects of crew size and blip/scan ratio were statistically significant for all dependent measures. The effect of trail length was not significant for any dependent variable. There was only one significant interaction. In terms of percent of scans with good tracking, increasing the trail length improved performance at the lower blip/scan ratios.

The surveillance simulation study was subsequently replicated with similar results using experienced military air surveillance personnel (3). The principal difference was that statistical significance of main effects was found for more dependent measures with the civilian subjects. The main effects of crew size and blip scan were statistically significant for civilian subjects but not for the military for the percent of aircraft initiated variable. On the other hand, in terms of the same dependent measure, trail length produced a significant effect for the military, but not for the civilian subjects. The difference in crew size effects was largely attributable to failure of the military to use a third crew member to as much advantage as civilians did. Effective allocation of surveillance subtasks was better achieved by the civilians, probably because they had more experience in working in three-man groups at the surveillance task.

In terms of the grand means, the military subjects took 55 seconds to detect and initiate automatic tracking on aircraft trails. The range was from 40 seconds for a three-man crew with a .9 blip/scan ratio to 76 seconds for a one-man crew with a .5 blip/scan. Comparable values for civilian subjects were a grand mean of 58 seconds and a range of 37 to 86 seconds for the corresponding crew size-blip/scan ratio combinations.

For overall percent of scans with good tracking the grand means were 41 and 43 percent for military and civilians, respectively. Again, the extremes for the ranges occurred at the same crew size-blip/scan ratio combinations as for first good initiate times and were 46-34 percent for the military versus 48-36 percent for the civilians.

In terms of percentage of targets detected and initiated, the best performance was achieved by the civilians and occurred at the .9 blip/scan ratio. The percentages of targets detected were 94, 95, and 98 for one-, two-, and three-man crews, respectively. The worst performance occurred with a .5 blip/scan at which civilian and military one- and two-man teams were equivalent (87 and 90 percent, respectively). Military three-man teams detected only 91 percent of the targets at the .5 blip/scan level, whereas civilian three-man teams detected 94 percent, which, you will note, is equivalent to one-man team performance with a .9 blip/scan ratio.

Even though there were discrepancies between military and civilian subjects, the nature and extent of the variations were not sufficient to invalidate conclusions drawn from research based on performance of trained civilian subjects using the surveillance system simulator. The differences were attributed to the civilian subjects' greater familiarity with the simulation. Therefore, the experiments confirmed the utility of research with the simulation for determining optimum mixes of hardware and crew capabilities and methods for effectively allocating functions among crew members.

WEAPONS DIRECTION SIMULATION

Background

The same computer simulation complex described above also was used to investigate human engineering design questions related to man-computer interaction in the weapons direction function of Air Force command control systems. The relationships between workload and data entry mode were of special concern to system designers and users. Users had strong preference for "light guns" or light-emitting pens for linking data to targets at the graphics interface. On the other hand, the use of a cursor, depicted on the graphic display and controlled via a track ball or joystick, offered possible advantages in accuracy of indications and hardware costs. Consequently, a weapons direction task simulation was developed and used to experimentally evaluate the alternatives (4, 5).

The weapons direction scenario was developed by an experienced weapons director working with computer programmers and research scientists. The task which resulted required the weapons director subjects to direct as many as 10 friendly interceptors or, fighters, against attacks by enemy, or "faker," bombers. Three levels of attack were investigated: a single "wave" of 16 bombers, two waves of 20 bombers each, and one wave of 40 bombers. Bombers entered from the west, or left, of the 200 200 mile surveillance area represented on the CRT and flew easterly toward a bomb release line (BRL) on the right about 185 miles from the entry line. Bombers entered at 500 knots airspeed and 40,000 feet altitude. (Bomber altitude varied from time to time according to a "canned" program.)

Five interceptors were "in the air" at the simulation start and were flying at 10,000 feet altitude and 500 knots airspeed. Five additional interceptors were available to the weapons director (WD) "on the ground" and were represented by an appropriate symbol to the right of the BRL. To "scramble" a fighter the WD had to designate it with the light pen or cursor. The WD could also "call for" changes in fighter altitude or airspeed via appropriate keyboard entries and light pen/cursor designations. Such changes were accompanied by appropriate variations in fuel use rate. Each fighter had 4500 pounds of fuel at simulation onset. A computer programmed algorithm controlled the fuel use rate which varied as a function of fighter speed and altitude in such a way that the maximum flying time of 44 minutes was achieved at 10,000 feet altitude and 180 knots. The minimum flying time was 15 minutes at 40,000 feet and 1080 knots. One minute before fuel level reached the minimum required for return to BRL, an F appeared in the fighter's symbology block.

The WD primary task was to use the fighter to intercept and destroy the attacking bombers. In doing his job, the WD could insert data which would result in heading, altitude, or velocity change; commitment or decommitment to interception of a particular bomber; or display of remaining amount of fuel and current velocity in the alphanumeric symbology block.

Upon being paired with a bomber, an interceptor was maintained on course automatically by a programmed intercept algorithm until within "kill" range, which included the requirement that both aircraft be at the same altitude. Altitude discrepancies resulted in automatic "de-commitment." Otherwise, a "kill" was credited with a probability of .75; i.e, in a random manner, one out of every four times "kill" range requirements were met, a de-commitment occurred, in accordance with expert estimates of the frequency with which "misses" might be expected. A "kill" was signalled by an "X" at the bomber position.

Experiment Design

The principal independent variable was data entry mode: light pen, track ball- or force stick-controlled cursor. The light pen used was the conventional device provided with the IBM 2250 graphics display system. The track ball and force stick were standard control devices procured from "off the shelf" stock. The principal dependent variables included number of bombers "killed," average distance from BRL at kill, amount of fuel used, and number of operator actions. Four experienced Air Force weapons directors served as subjects in a repeated measures experiment.

Results

Analysis of variance showed that the main effect of data entry mode was significant ($p < .01$) for 3 of the 4 principal dependent variables. The main effect of workload (number of bombers) was significant for all four dependent variables.

The light pen consistently showed advantages over the other two data entry modes and the track ball was better than the force stick more often than not. The superiority of the light pen was greatest when the workload was heaviest, i.e., when there were 40 bombers to be intercepted. The advantage was attributable to the greater speed with which data entry actions could be taken with the light pen mode.

Mean numbers of the bombers destroyed prior to reaching the BRL are shown in Table 1. Averaged across the three workload levels, the WDs obtained, on the average, 91, 83, and 75 percent "kills" under the light pen, track ball, and force stick conditions, respectively. The WDs were least effective in dealing with one wave of 40 bombers, obtaining, on the average, 78 percent kills as compared to 82 percent and 99 percent kills for two waves of 20 and one wave of 16, respectively.

Table 2 shows the average distance (miles) from the BRL at which "kills" were made for each experimental condition. Again, note that the greatest advantage was for the light pen over the track ball was at the two higher workloads.

Table 3 shows means for pounds of fuel used by the interceptors. The increased speed with which information was transmitted to fighters via the light pen mode was reflected in less flying time, fewer instances of high speed chases, and hence, reduced fuel use. The differences were statistically significant between light pen and track ball and between light pen and force stick.

Means for the number of actions initiated by WDs per experimental condition are shown in Table 4. It was primarily the increased time required to execute cursor movements which restricted the effectiveness and efficiency of WDs in achieving the mission objective with the track ball and force stick modes. Note that under the 16-bomber attack, where effectiveness varied little across data entry modes, the number of operator actions varied little across modes.

The added efficiency of the light pen is reflected better, perhaps, by Table 5, which shows the average action rate (number of actions per 10-second computer update interval) for each condition. The track ball and force stick action rates were, respectively, 32 percent and 46 percent less than the average light pen rate.

Obviously, the speed with which the data entry modes are used could have been, and, in fact, was, evaluated without benefit of the weapons direction simulation. The advantage of accomplishing the test within the context of the system simulation was in being able to relate differences to overall system effectiveness in terms of critical system performance criteria and operating costs and under a range of environmental conditions.

TABLE 1. PERCENT OF BOMBERS DESTROYED

	Workload (No. Waves/Bombers per Wave)		
Date Entry Mode	1/16	2/20	1/40
Light Pen	16.00	36.75	34.75
Track Ball	16.00	33.00	30.75
Force Stick	15.75	28.25	28.00

TABLE 2. AVERAGE DISTANCE FROM BOMB RELEASE LINE AT "KILL" (miles)

	Workload (No. Waves/Bombers per Wave)		
Date Entry Mode	1/16	2/20	1/40
Light Pen	107	78	72
Track Ball	98	59	55
Force Stick	82	47	50

TABLE 3. AVERAGE AMOUNT OF FUEL USED (Thousands of Pounds)

	Workload (No. Waves/Bombers per Wave)		
Data Entry Mode	1/16	2/20	1/40
Light Pen	11	24	24
Track Ball	18	33	27
Force Stick	19	31	29

TABLE 4. AVERAGE NUMBER ACTIONS INITIATED BY WEAPONS DIRECTORS

	Workload (No. Waves/Bombers per Wave)		
Data Entry Mode	1/16	2/20	1/40
Light Pen	85	161	152
Track Ball	93	130	107
Force Stick	86	104	96

TABLE 5. AVERAGE WEAPONS DIRECTOR ACTION INITIATION RATE (Actions per 10-Second Interval)

	Workload (No. Waves/Bombers per Wave)		
Data Entry Mode	1/16	2/20	1/40
Light Pen	1.2	1.1	1.2
Track Ball	0.9	0.8	0.7
Force Stick	0.7	0.6	0.6

COCKPIT-DIGITAL AVIONICS SIMULATION

Background

The evolution of compact digital computers has made possible the development of digital avionics information systems. Such systems promise a number of advantages to both aircraft designers and users (6). For example, when interfaced with multipurpose cathode ray tube displays and multifunction switches, digital computation and storage capabilities can be used to reduce the number of dedicated instruments competing for cockpit panel area. Information which is not required by the pilot on a continuous or frequent basis can be stored and presented on demand either automatically, as related programmed mission events transpire, or in response to manual control actions. And with reduced demands for panel space, it will be easier to locate the multipurpose controls and displays in prime reach and viewing areas.

However, experienced pilots have been troubled by the prospect of possible added activity—both mental and physical—required to gain access to information which is normally on dedicated instruments. Should the demand for such activities occur during peak operator workload, the impact on mission success might not be offset by increased calculating power, speed, or accuracy afforded by the digital processor. The need for data indicative of the relationship between multifunction switching and primary aircraft control tasks and the impact on pilot workload occasioned the adaptation of the AFAMRL computer complex to simulate a digital avionics equipped cockpit (7). Of particular interest was whether or not the maintenance of knowledge of procedures associated with multifunction keyboard operation reduced the operator's reserve capacity for making choices or decisions such as might be required to handle contingency situations during a mission.

The computer-based simulator incorporated three types of tasks. Of the three, two—flight control and communications/IFF switching functions—represented actual tasks in aircraft systems. The third was an information processing task which served as a test to measure cognitive reserve capacity under various primary task conditions.

The front panel of the cockpit was equipped with three CRT-type displays. The center display was used to present information concerning basic flight parameters in a moving tape format. The cockpit also contained a throttle with afterburner switch (left side panel) and a center-mounted joystick control, which were used, in combination with the displayed flight information, to "fly" various maneuvers. Printed computer outputs of simulator performance data included both mean absolute and root mean square error relative to specified control values based on "fly to" instructions for altitude, heading, bank angle, pitch, indicated airspeed, vertical velocity, angle-of-attack, and g-load.

Between the front instrument panel and left side panel was a multifunction keyboard (MFK). This MFK, in combination with the CRT on the upper left of the front panel and a numerical entry keyboard, also located on the instrument panel (lower left), was used to simulate a multifunction interface with digital avionics subsystems. Subsystems, functions, and states were displayed on the CRT to complement the feedback afforded by back-projected legends on the MFK pushbutton faces. The MFK was used to control communication and IFF functions called for by scenarios programmed on the simulator.

The reserve capacity test used was a variation of the Sternberg choice reaction task (8, 9). This particular task was selected on the basis of its value for studying divided attention effects, i.e, the tendency for subjects who perform two tasks simultaneously to be less proficient on one (if not both) than they are when performing the tasks separately (10, 11). The Sternberg task facilitates localization of the divided attention effect within a four-stage model of human information processing: encoding of stimulus information; central processing; response decoding; and response execution. The Sternberg task allows the researcher to vary central processing demands while holding input and output requirements constant. The data obtained from the task are used to develop a linear equation indicative of the relationship between response latency and the amount of uncertainty which must be resolved in order to select a response.

Briggs and Swanson (12) found a linear relationship between Sternberg task reaction time (RT) and the amount of central processing uncertainty (H_c) thus:

$$RT = a + b\ (H_c)$$

H_c values used in the study of multifunction switching were: 1.00, 1.50, 2.00, and 2.31 bits.

In the equation for reaction time (RT), the intercept constant, a, reflects the time required for stimulus encoding, sampling, and preprocessing at the input stage of human information processing plus the time to decode and execute a response in the output stage; the slope, b, reflects the time per test to complete stimulus classification functions at the central processing stage. Therefore, if a task performed simultaneously with the Sternberg task interferes with encoding or decoding processes, its effect should be reflected by a change in the intercept value. Conversely, if the interference occurs at the central processing stage, the effect will be revealed by a change in the slope of the function.

Experiment Design

Data were derived from the performance of four student subjects in the simulator. Prior to the experiment proper each subject was trained on all three tasks. Training sessions lasted 2 hours and were scheduled two to four times per week. Each subject was trained until task performance measures appeared to asymptote.

Each subject was tested under six different conditions: three single-task conditions and three dual-task conditions: Flight control, MFK, and Sternberg choice-reaction task, alone; and flight control plus MFK, flight control plus Sternberg task, and MFK plus Sternberg task. When the Sternberg task was combined with MFK, it occurred only during periods when the subject was awaiting instruction for an MFK task of a given difficulty level. This was consistent with the interest in measuring cognitive loads associated with anticipating, rather than actually performing, MFK tasks. Independent variables included two levels of flight control task difficulty ("easy" and "difficult") and four levels of MFK task difficulty measured in terms of the average amount of information transmitted via the keyboard in accomplishing communications/IFF functions.

Results

An analysis of variance (repeated-measures design) was applied to scores obtained for each condition. Results from the single task conditions were as follows: The difference between easy and difficult flight control was statistically significant ($p < .05$). The effect of MFK task difficulty also was significant statistically ($p < .001$). Mean task times (in seconds) and standard deviations (in parentheses) for the four difficulty levels were: I-3.97 (0.32); II-5.95 (0.53), III-7.43 (0.68), IV-9.87 (0.83). The average rate of information transmission via the MFK system varied from 1.8 bits/sec to 2.6 bits/sec across the four levels of MFK task difficulty. The switch action rate was slightly greater than one per second on the average. The method of least squares was used to fit a straight line to the baseline (single task) Sternberg data.

Data analyses for the dual-task conditions showed that although mean flight control error was greater when flight control was combined with MFK tasks, the differences were not statistically significant. Similarly, MFK task times increased under dual task conditions, but the increases were not statistically significant. Flight control error scores were virtually identical for flight control alone as compared to flight control with the Sternberg task. And the Sternberg task had no statistically significant impact on MFK task time. Linear equations also were fitted to Sternberg response time data for each dual-task condition to permit comparison of intercept and slope values with those obtained for the Sternberg task baseline condition. F-tests (13) indicated that slopes and intercepts for the flight control conditions differed significantly from those for the baseline condition, and intercept value varied significantly between the baseline and MFK implicit rehearsal condition. Interpreted in the traditional manner, these results indicated that the effect of MFK "implicit rehearsal," i.e., maintaining a readiness to perform anticipated tasks, was in the input or output stage of information processing only. Following the empirical evidence and logic of Briggs et al. (11), the effect is probably in the input stage. The difference in intercept values amounted to a 12 percent average increase in input time attributable to MFK "implicit rehearsal."

Active flight control, on the other hand, involved both input and central processing as evidenced by differences from baseline in both intercept and slope values for the regression equation. Moreover, there was an increase in input-output time (28 percent and 55 percent for easy and difficult flight control, respectively) and an increase in central processing rate. The increase in central processing rate under the dual-task condition, which was consistent with results obtained by Lyons and Briggs (Briggs et al., 1972), was attributed to the subject's conducting fewer or less complete tests of the probe stimulus under the greater loading conditions. This apparent switch in mode of operation in the central processing stage, between single- and dual-task conditions, could be a valuable aid to identification of significant workload changes.

A comprehensive analysis of information transmitted via the Sternberg task indicated that difficult flight control reduced reserve information processing capacity of the pilot by 54 percent; easy flight control, by 45 percent; anticipation of difficult MFK tasks, by 31 percent; and easy MFK tasks, by 20 percent. Thus, although MFK tasks may be compatible with moderately difficult flight control requirements, they do place significant demands on cognitive abilities and may detract from the pilot's ability to cope with high workloads in critical combat situations. Therefore, concerted efforts to simplify the control/display interface to digital avionics subsystems are warranted and are probably best accomplished in computer-based system simulations which facilitate development and evaluation in an iterative manner and under a wide range of mission conditions.

USER-ORIENTED SYSTEM DESIGN

Although generic design principles may be derived from simulation experiments like those described above, the studies were designed to address specific issues in particular systems. System-specific simulations must meet at least two important criteria: timeliness and cost-effectiveness. Requirements must be identified early in the design process if large system simulations are to be developed and applied in a timely manner. Cost-effectiveness may be difficult to assess with confidence prior to the actual simulation results. Even when cost-effectiveness is assured, system simulation may be prohibited by limited funding. A recent workshop (14) on man-computer interface design provides some useful suggestions with regard to meeting system design goals within schedule and cost constraints.

Top-Down Approach

The application of a "user-oriented" top-down approach to computer system design will facilitate identification and resolution of human engineering design issues in a timely manner. The essence of such an approach is outlined in

Figure 1. Note that the approach entails three basic processes: analysis, synthesis, and evaluation. Simulation is the vehicle by which models of system functions are exercised to obtain inferences, predictions, and evaluations prior to production. It is suggested that current computer system design and evaluation techniques are largely empirical and highly dependent upon the experience and skills of those who apply them. The top-down approach is the bridge to more objective and systematic methodology, but it requires an adequate technology base.

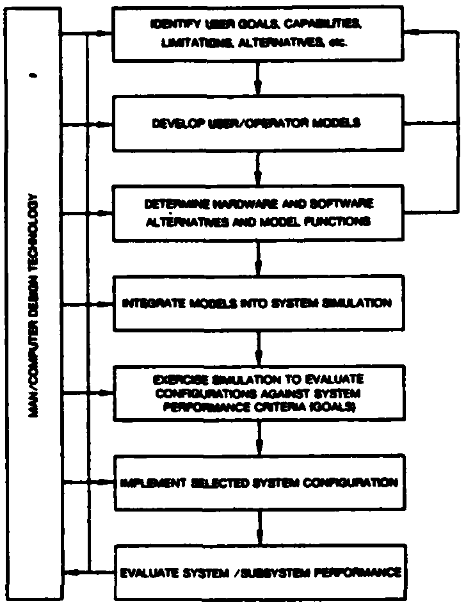

Figure 1. A Top-Down Approach to Man-Computer System Design

Man-Computer Design Technology

Processes of the user-oriented top-down approach cannot be accomplished successfully without benefit of relevant data inputs and structural aids. For example, analysis of system requirements depends upon the capability to identify component tasks and associated input-output relationships. Hence, the first requirement to be met in technology base development is a standard taxonomy of information processing functions including a generic set of user tasks and algorithms definitive of inter-relationships. The same technology base also would support the synthesis and evaluation processes including modeling and simulation. It would also be generally applicable to a wide variety and number of computer-based systems (15).

Man-computer interface design technology development requires a long-term effort, but significant beginnings have been made. Computer functions are relatively easy to analyze and measure in terms of information theory concepts and metrics. Behavioral scientists also have applied information theory to the analysis and quantification of certain human capabilities (16). Some of the problems yet to be overcome in relating human and machine information processing capabilities have been identified and discussed by Crawford, Topmiller, and Kuck (17). Rudimentary efforts to apply human performance theory to the development of a generic set of human information processing functions have been summarized by Crawford (18).

The advent of microprocessors, inexpensive graphics, and distributed processing now facilitates emphasis on adaptation of computer to man. The costs and complications of user errors and extensive user training programs, which result from over reliance upon adaptation of man to computer "idiosyncrasies," cannot be justified indefinitely. The "zeitgeist" is right for concerted efforts to facilitate man-computer symbiosis in future systems.

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